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ABSTRACT

We present a novel approach for linear polarized operation of a fiber laser not requiring any intra-cavity components, but relying on an external self-seeding effect. A small fraction of back-reflected polarized light created in an external cavity consisting of fused coupler, polarizer and fiber Bragg grating is sufficient to seed and lock the laser to linear polarized operation. This approach enables the construction of polarized monolithic fiber lasers, minimizes intra-cavity losses and drastically reduces parasitic amplified spontaneous emission. We experimentally demonstrate strong polarization locking in an Yb-doped fiber laser with extinction ratio of 500:1 at 1154 nm.

Keywords: External polarization locking FBG cavity non-standard wavelength Yb-doped fiber laser

1. INTRODUCTION

Injection locking techniques are used for several applications, such as wavelength locking of laser diodes[1–3] as well as polarization locking in He-Ne lasers[4] and fiber distributed feedback (DFB) lasers.[5,6]

We present a novel approach for linearly polarized operation of a continuous-wave (CW) fiber laser using the self-injection technique. Linearly polarized continuous wave laser sources are essential for a wide range of applications, such as efficient second harmonic generation (SHG). A standard approach to achieve linear polarization is to introduce an inline polarizer into the laser cavity. However, this approach increases the intra-cavity losses, significantly reduces the efficiency of the laser, and the spurious reflections at the splice points and end facets of the polarizer can lead to detrimental parasitic lasing effects, especially when laser operation is desired at wavelengths far away from the gain maximum.

In this work, we focus on the especially difficult scenario of operating an Ytterbium-doped laser at the long-wavelength edge of the gain window at 1150 - 1170 nm. Sources at these wavelengths are currently investigated for SHG to the visible yellow-orange spectral range. Several applications such as artificial laser guide stars,[7] surgery[8] or quantum optics[9] demand for Watt level CW laser sources in this visible wavelength range. At wavelengths around 1150 - 1170 nm, the achievable upper limit of the laser output power is mainly limited by strong amplified spontaneous emission (ASE) and parasitic laser emission at wavelengths around the gain maximum of 1030 nm. Here we show that a new self-injection linear polarization scheme, where the polarizer is placed outside of the laser cavity, delivers a significant performance increase when compared to the traditional placement of the polarizer inside the cavity. Specifically, ASE and parasitic laser emission due to spurious reflections are avoided, leading to an increase of power extractable from the laser cavity.

2. SETUP

In a previous work[10] we demonstrated such a laser cavity setup as depicted in Figure 1a. In order to enforce the operation of the laser cavity at 1154 nm, a set of matched high and low reflective fiber Bragg gratings (FBGs) and heating of the Yb-doped fiber is crucial for suppressing the unwanted process of ASE. This setup allows us to generate 5 Watt of laser emission at a wavelength of 1154 nm. The laser is pumped by a 976 nm not wavelength stabilized pump diode which is spliced to a pump-signal combiner. The pump-signal combiner guides the pump light into a 6/125 μm double clad fiber, where the high reflective FBG is spliced. At the other end of the pump-signal combiner is a 6/125 μm single clad fiber, which allows to monitor the

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backward propagating light coming from the cavity. The gain medium is a 4.5 m long Yb-doped fiber, which is heated to a temperature of 150 °C in order to shift the absorption as well as the emission spectrum towards longer wavelengths.[11] Within the cavity there is an inline polarizer which transmits the signal on the slow axis and blocks it for the fast axis. The end of the cavity is a out-coupling FBG with a reflectivity of 57 % at 1154 nm. The limitation of this setup is the arising ASE for increased pump power.

Our new design approach is depicted in Figure 1b. It significantly reduces the intra-cavity losses by moving the inline polarizer out of the cavity. After the main laser cavity a fused coupler is introduced followed by the inline polarizer and a high reflective FBG. Both components are placed at the couplers low power port (10 %), while the high power port (90 %) serves as the laser output. A fraction of the laser signal therefore becomes linearly polarized and is reflected back by the high reflective FBG. Unwanted ASE passes through the FBG and is dumped. The reflected light passes the polarizer a second time and is coupled back into the laser cavity, which causes self-injection linear polarization locking.

In both setups, all the FBGs are mounted on a stretching unit, which allows to fine-tune the reflected wavelength of the FBG by applying a tension to them.

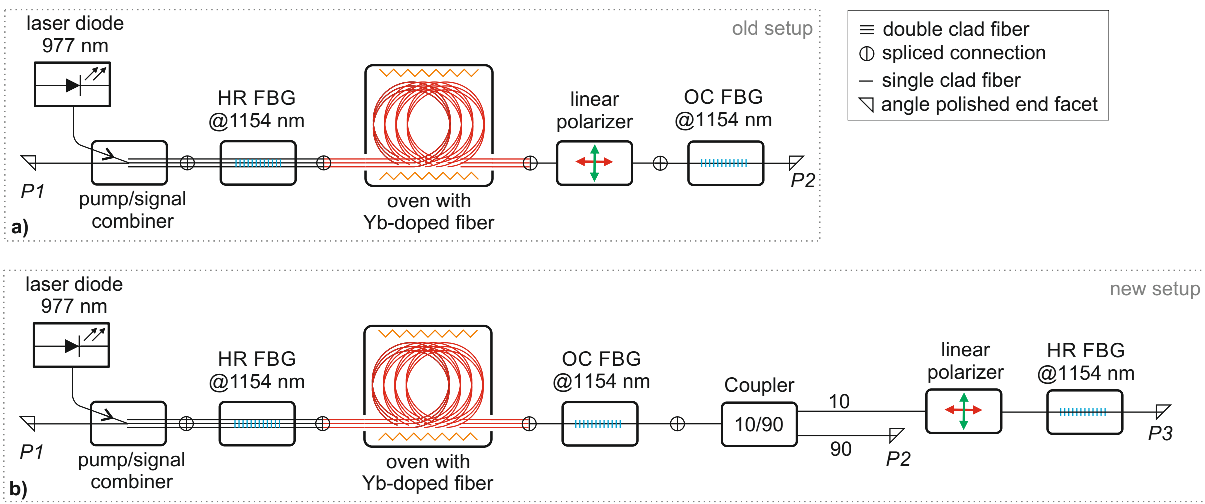

Figure 1: Conventional vs. self-injection locking scheme: a) illustrates to old setup, where the inline polarizer is places within the cavity. b) illustrates the new setup, where the inline polarizer has moved out of the cavity.

Figure 2 illustrates the measurement setup, all the ports correspond to the ports from figure 1b. Port P1 allows to measure the backward propagating signal of the cavity, namely the backward ASE. The signal exits the fiber at the angle polished end facet and propagates as a divergent free space beam. A part of this light is then coupled into a 50/125 μm multi-mode fiber which is connected to an optical spectrum analyzer. The same method was applied at port P3 in order to measure the signal coming from the cavity, which passed the inline polarizer once. This port is mainly used to monitor the forward propagating ASE. The signal at port P2 is roughly collimated with a lens and passes a half wave plate before beeing split up into the two polarization orientations. These are then measured with two power meters.

Spontaneous laser emission at the gain maximum of Ytterbium occurs if the power of the parasitic ASE reaches a certain limit, resulting in a high output power due to the increased efficiency. Therefore, to prevent damage to the optical spectrum analyzers, the signals at port P1 and P3 were measured uncollimated, as described above.

The new design has three main advantages: (i) the loss of the cavity is reduced to a minimum and thus the parasitic ASE and spurious reflections at splice points are significantly reduced. Without the polarizer in the cavity we are able to generate 10 Watt of ASE-free randomly polarized 1154 nm light. Even monolithic

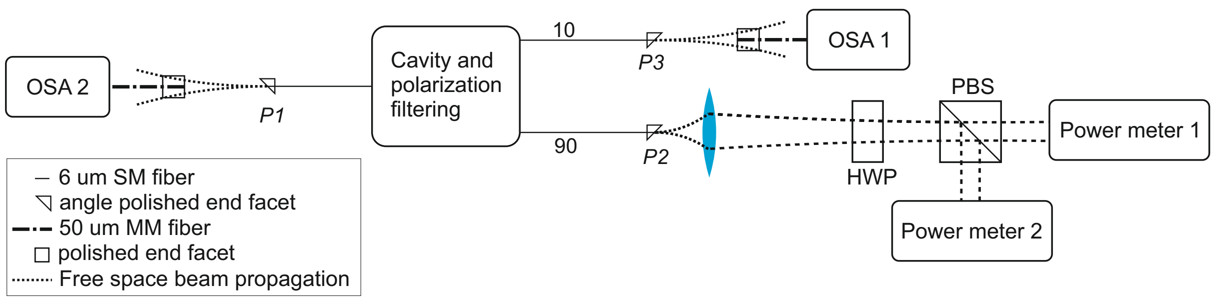

Figure 2: Measurement setup. The setup allows to measure the backward propagating signal at port P1, monitor the cavity signal at port P2 and measure the power of each polarization state.

cavity designs by inscribing the FBGs directly into the doped fiber are easy to envisage. (ii) a low-power in-line polarizer can used. Placed inside the cavity, the polarizer must be able to deal with a total optical power of more than 50 Watt, assuming 10 W of 1154 nm output in our system. Externally placed, the optical power after the coupler will be approximately 20 times lower. (iii) the system provides an additional monitoring port of the 1154 nm signal, which can be used to fine tune the system and survey the potential presence of the ASE.

3. RESULTS

The measurements were recorded with a self developed software written in MATLAB and repeated five times. Therefore, no real-time adjustments, such as tuning the temperature of the pump diode or fine-tuning of the Bragg gratings, were done. Furthermore, each measurement was performed under the same condition: the pump diode was switched on and off for every single measurement. This decreases systematic errors such as a thermal history of the components, requires, however, a not yet performed long term stability measurement. Additionally, all given values for the pump power correspond to the power available at the fiber output of the pump diodes.

The output power series is presented in figure 3a. The error bars indicate 1σ standard deviation (STD). Noticeable is the increase of the P-oriented polarization power between 6 and 10 Watts. This implies the smaller ratio mentioned above. For the sake of detail information, the power series of the P-oriented polarization is depicted alone in figure 3b.

The polarization extinction ratio with respect to the pump power, derived from the power values shown in figure 3a is depicted in figure Figure 4. The error bars indicate the standard error of the mean (SEM). Considering the entire pump series, the polarization ratio varies considerably with respect to the launched pump power. Between 6 and 10 Watts of pump power, the ratio is at a low extinction ratio, for higher pump power, the ratio increases. Furthermore, the effect of polarization locking is lost for pump powers higher than 19 Watts; the ratio reduced to a value of 1.

The evolution of the signal spectrum at the wavelength around 1154 nm, recorded at port P3, is depicted in figure 5. It shows a narrow-banded laser emission line with a bandwidth of 0.06 nm measured at a level of -3 dB from the peak. The output signal grows continuously with increasing pump power. The axis of the ordinate is logarithmic, however, the signal is attenuated due to the design of the setup.

Additionally, the evolution of the optical spectrum for the forward propagating signal, recorded at port P3, is depicted in figure 6. The signal at the wavelength of 1154 nm is attenuated by the high reflective (99.9 %) FBG located before the end facet. Therefore, the values of the signal at a wavelength of 1154 nm are not proportional to the values of the rest of the optical spectrum. The optical spectra show the continuous increase of the 1154 nm signal, indications for an upcoming ASE (figure 6e) at wavelengths between 1050 and 1100 nm and the absence of non linear effects, such as Raman scattering.

Finally, figure 7 shows the evolution of the optical spectrum for the backward propagating signal at port P1, which corresponds to the backward ASE. The wavelength range of the used optical spectrum analyzer

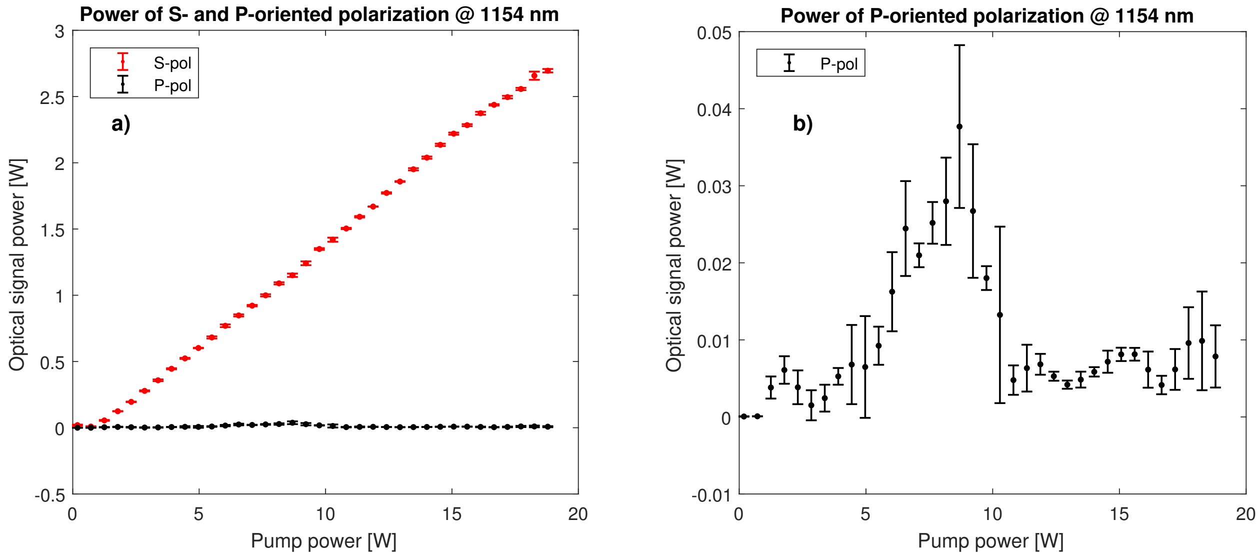

Figure 3: a) Power series of the averages values of the two polarizations S and P with 1σ standard deviation (STD) error bars. The signal is at a wavelength of 1154 nm. b) Power series of the P-oriented polarization only with 1σ standard deviation (STD) error bars.

(OSA 2) is limited to an upper wavelength of 1120 nm. Therefore, the backward propagating 1154 nm signal is not visible. Furthermore, the resolution as well as the signal to noise ratio is smaller than for OSA 1. However, the spectrum show an upcoming ASE between wavelengths of 1050 to 1070 nm for increased pump power. Additionally, the spectrum show some pump light, which propagates in the opposite direction of the pump. It is most likely caused by scattering at the splices. For the sake of visibility, the units of the ordinate axis were set to linear scale.

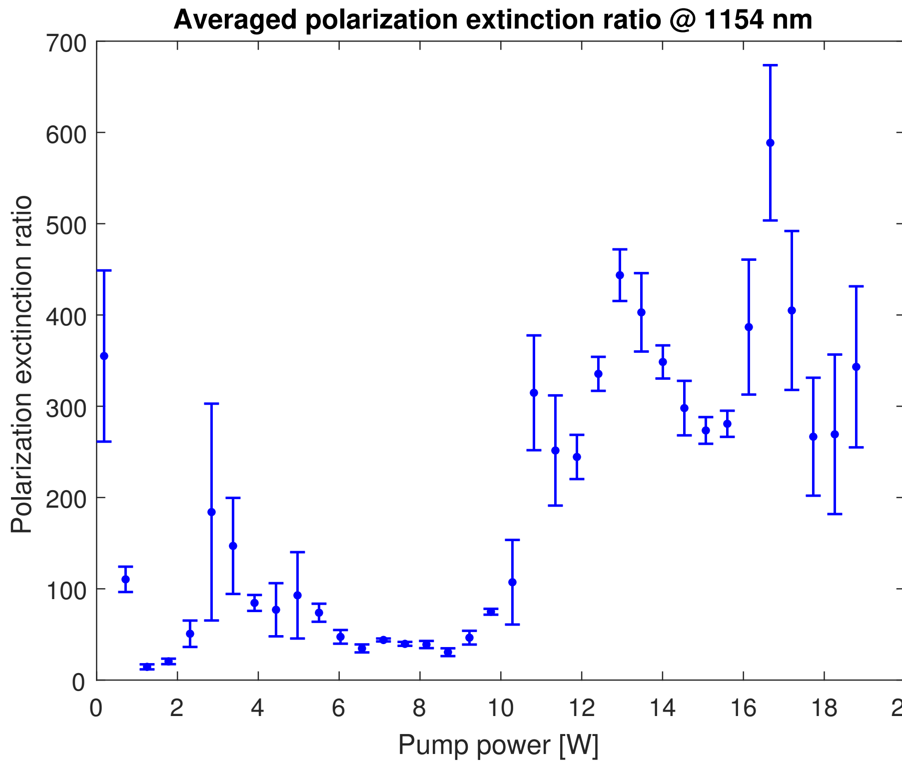

Figure 4: Polarization extinction ratio of the mean values. The error bars represent the standard error of the mean value (SEM).

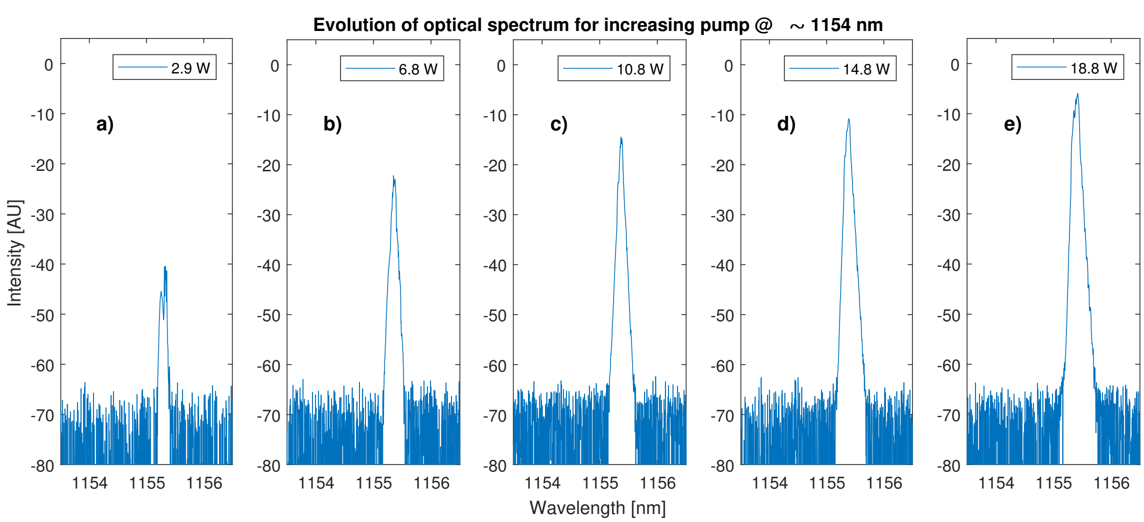

Figure 5: Evolution of the optical spectrum of the laser emission signal. The calculated bandwidth at -3 dB is 0.04 nm for a, b and c and 0.06 nm for d and e.

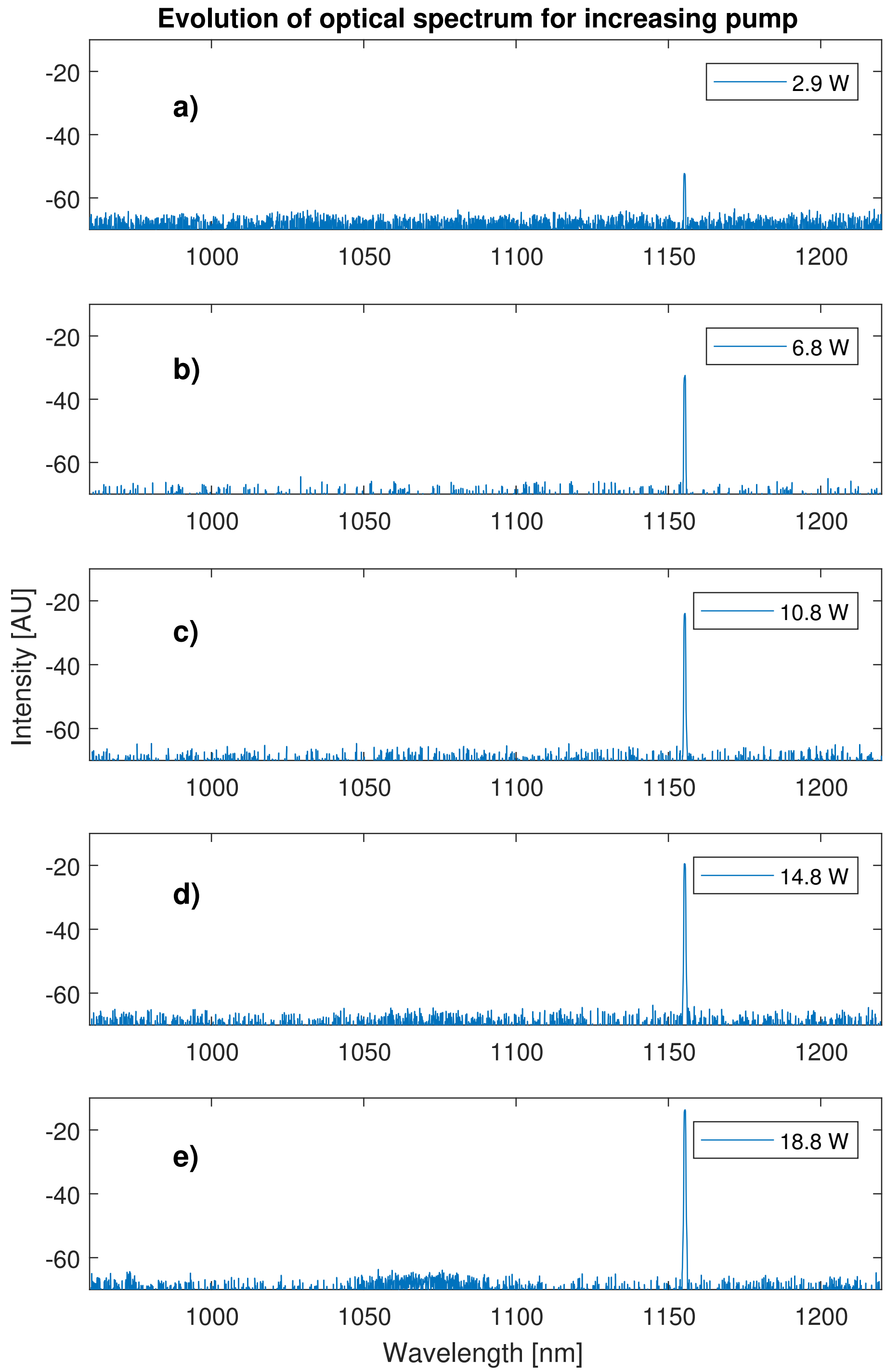

Figure 6: Evolution of the forward propagating optical spectrum. It shows the absence of forward ASE and any kind of Raman scattering. Only plot e) shows the beginning of upcoming forward ASE.

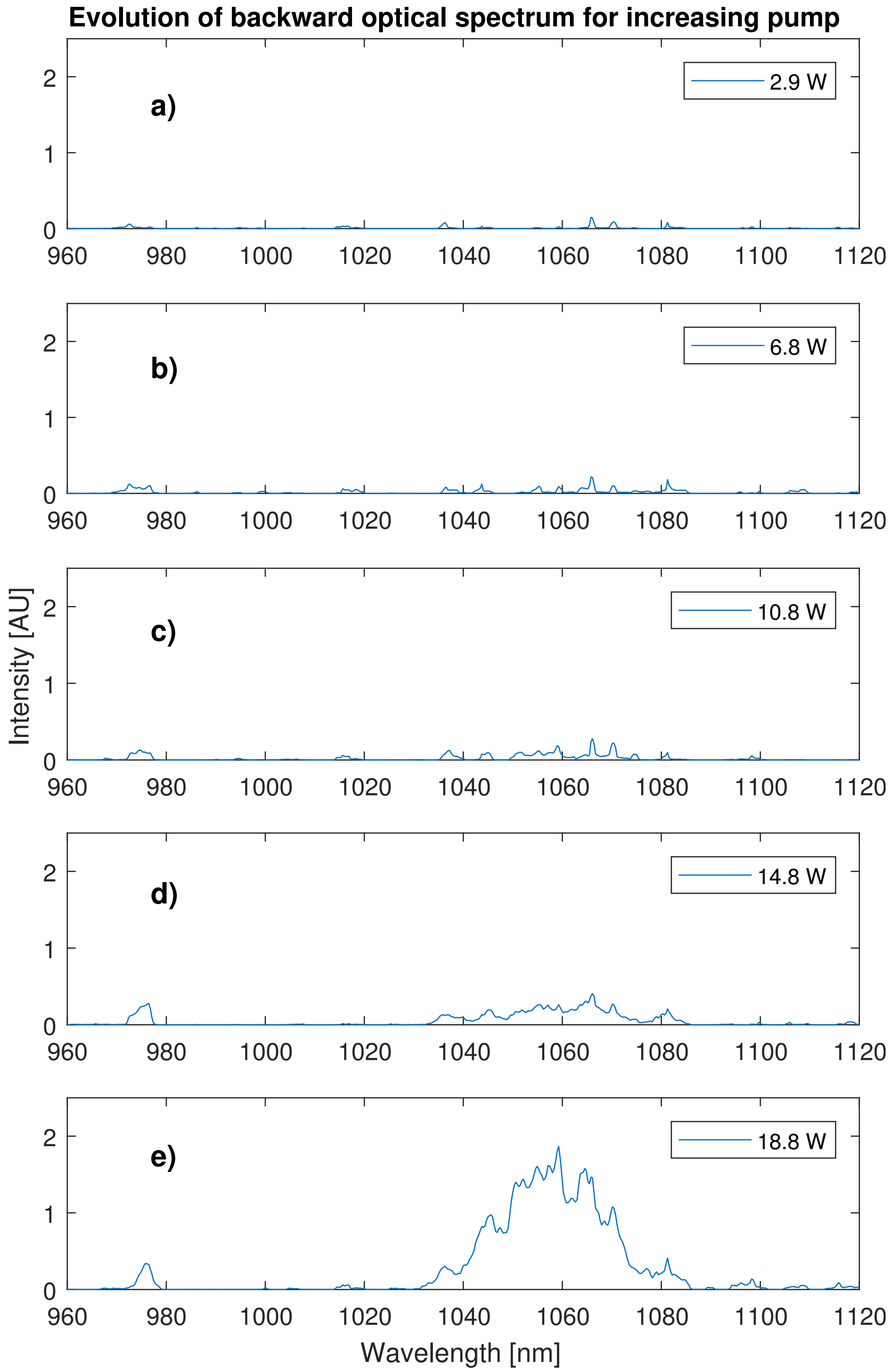

Figure 7: Evolution of the backward optical spectrum, which mainly consists of ASE.

4. DISCUSSION

To our best knowledge such an all-in fiber self-injection polarization locking laser has not yet been demonstrated. With our new setup we are able to generate linearly polarized laser emission at an extinction ratio of 500:1 at an output power of more than 2.5 Watt. We were able to generate this laser emission at the long-wavelength edge of the Ytterbium gain window, nevertheless, the setup could be run at a large variety of desired wavelengths. However, the effect of self-injection polarization locking gets lost for pump power higher than 19 Watt.

Although figure 4 show some fluctuations in the polarization extinction ratio, considering the power series in figure 3a demonstrate that the setup locks the orientation of the polarization of our cavity a minimum ration of 50:1. Moreover, the power series of the P-oriented polarization in figure 4b show firstly, that the power is at a very low level and secondly an increase of power between the pump power of 6 to 10 Watt. These larger values explain the smaller errors of the polarization extinction ratio calculations.

The loss of the polarization locking above a pump power of 19 Watt comes most likely from the fact, that the feedback signal is too small compared to the intra-cavity signal. To overcome this limit, another coupler with a ratio of e.g. 20/80 could hence be used. However, this has not yet been tested and requires therefore further investigation.

The proof that the system actually locks the polarization was done by applying a tension to the filtering FBG next to port P3. Once the reflected wavelength of this FBG did not overlap the wavelength of the cavity anymore, the extinction ratio dropped immediately to a value close to 1, which corresponds to an unpolarized system.

Nevertheless, the system produces a narrow-banded laser emission line at a wavelength far away from the gain-maximum of an Yb-doped fiber. The bandwidth of the peak emission has a measured value of 0.06 nm at -3 dB. From the optical spectrum, we know that the system does not generate parasitic ASE. Figure 6e shows the appearance of some low power ASE between the wavelength of 1050 to 1100 nm. However, this optical spectrum was recorded at port P3 (figure 1b), where the signal peak at 1154 nm is attenuated due to the fact, that 1154 nm laser light is reflected at the 99.9 % FBG. Therefore, the ratio of signal power to ASE power at port P2 is even larger in reality.

Our new approach of self-injection polarization locking could be used as a seed signal for subsequent fiber amplifier stages, where it is crucial that the seed signal does not contain any ASE.

5. CONCLUSION AND OUTLOOK

We successfully demonstrated the proof-of-principle for an self-injected single polarization fiber laser for a wavelength far away from the gain maximum. The system generates a reproducible laser emission signal at an output power of 2.5 Watt at a wavelength of 1154 nm. However, the polarization locking becomes unstable at higher power levels and needs therefore further investigations.

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